

SUPERCONDUCTING MAGNETS EXERCISES - FEM

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- This is a 6 hour module, spilt in two days (3+), and repeated four times
 - Each time it is given to about 25 participants
- The six-hour module is structured as follows
 - Day 1:
 - 30 minutes: recap of the main equations, plus exercise description
 - 2 h: exercise on analytical tools
 - 30 minutes correction and discussion
 - Day 2:
 - 30 minutes: tutorials about how using a finite element model, plus exercise description
 - 2 h: exercise on finite element tools
 - 30 minutes corrections and discussion

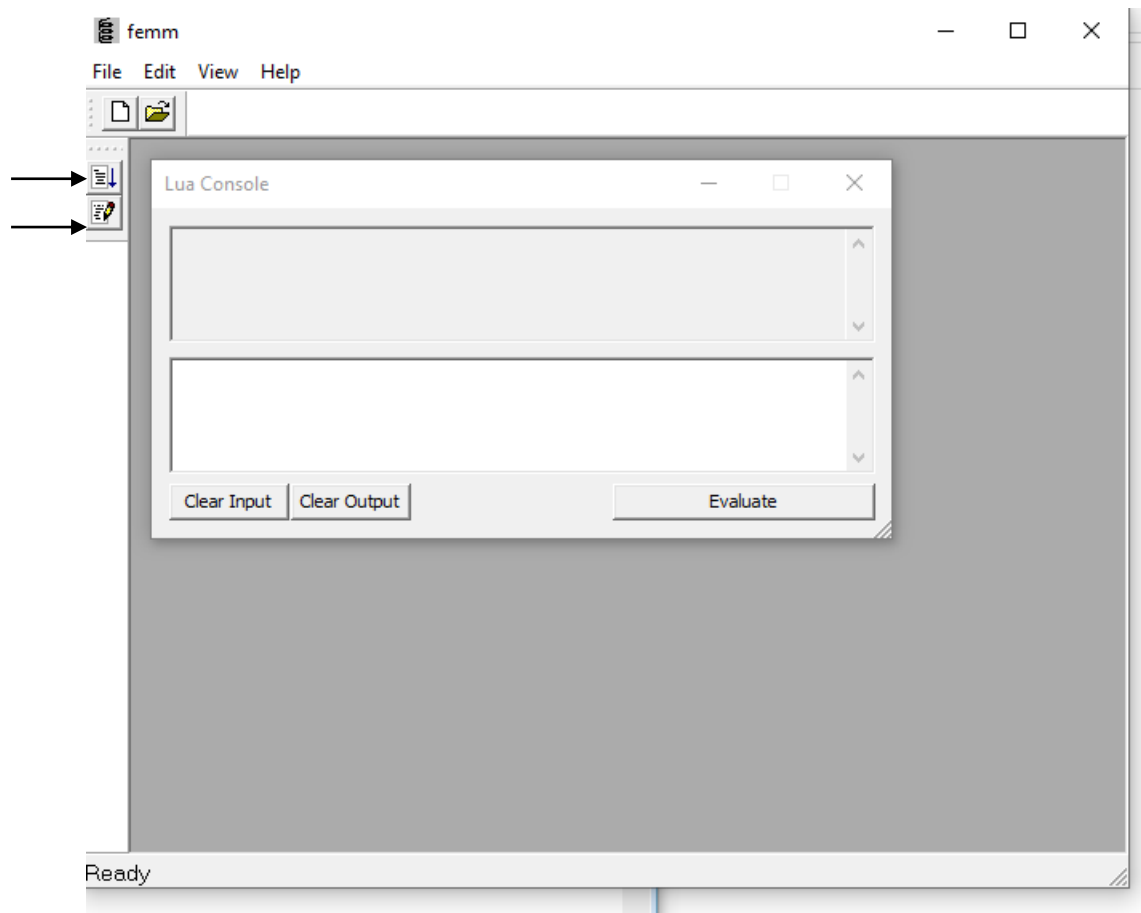
- Day 1
 - Recap of the theory
 - Exercise
 - (solutions in a separate word file)
- Day 2
 - The FEMM code
 - Exercise

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- Finite Element Method Magnetics (FEMM) written by David Meeker is a finite element package for solving 2D planar and axisymmetric problems in low frequency magnetics and electrostatics.
- The program can be obtained via the FEMM home page at <http://www.femm.info/wiki/HomePage>. The package is composed of an interactive shell encompassing graphical pre- and post-processing, a mesh generator, and various solvers.
 - User manual: <https://www.femm.info/Archives/doc/manual42.pdf>
- A scripting language, Lua , is integrated with the program. Lua allows users to create batch runs, describe geometries parametrically, perform optimizations. It is available from <http://www.lua.org>.
 - User manual <https://www.femm.info/Archives/doc/refman-4.0.pdf>

- To save a bit of time, we prepared some scripts
 - sector_dipole.lua
 - multipoles_femm.lua

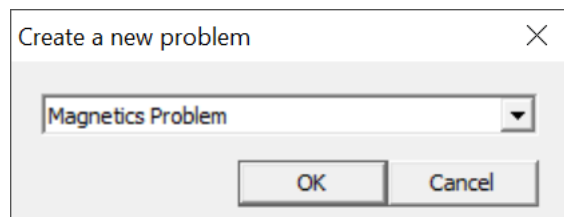
Run a Lua script
Launch a Lua script



1. Create a new file, “magnetics” category and set main problem parameters
2. Set few variables
3. Load or prepare material properties, boundary conditions and circuit elements
4. Define geometry
5. Save and mesh
6. Solve
7. Post-process

---> File ---> New

---> Problem



1 m depth, so results (energy, inductance, force, ... will be per m length

-- Creates a new preprocessor document (magnetics problem)

`newdocument(0)`

-- Main problem parameters

-- 0 frequency

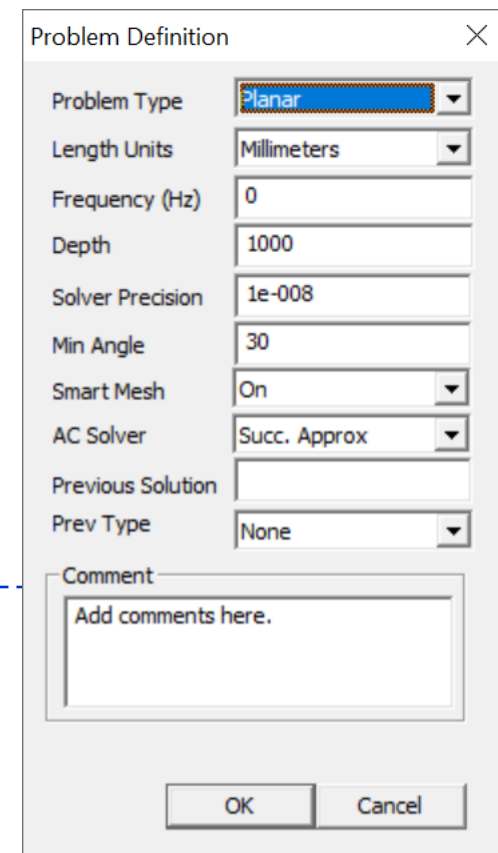
-- mm units

-- planar problem

-- solver precision

-- depth, set to 1 m so to have results per m length

`mi_probdef(0, "millimeters", "planar", 1e-8, 1000)`



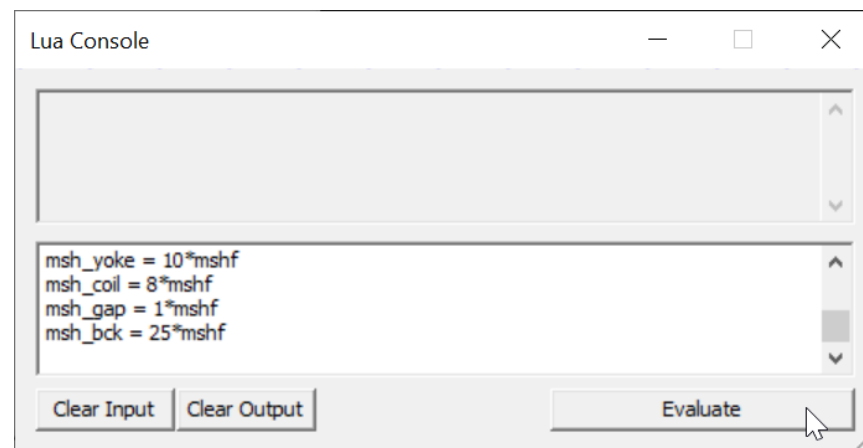
Write (or copy & paste) in Lua console, then click Evaluate

```
-- A few variables
pi=3.141592653589
aperture = 50
w_coil = 15
alphad_coil = 60
alpha_coil = alphad_coil*pi/180
w_collar = 65-aperture/2-w_coil
w_iron = 134-aperture/2-w_coil-w_collar
w_air = 400
workfolder = "\\cernbox-smb\eos\user\s\suizquie\conferences\2311_CAS\Exercise\FEMM\final"
filename = "sector_dipole_exercise.fem"

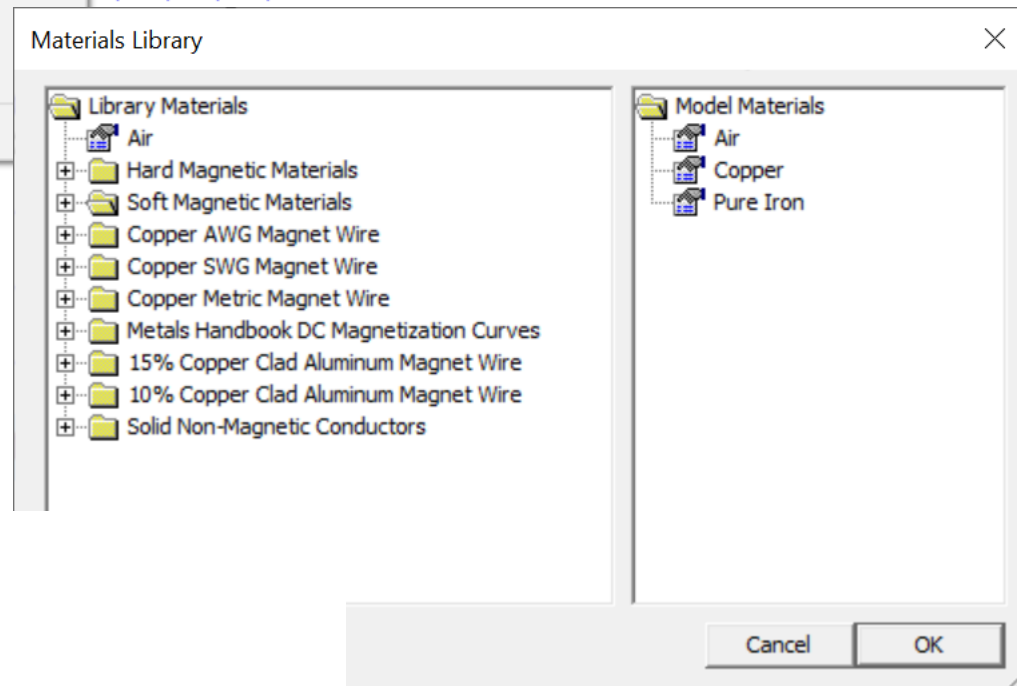
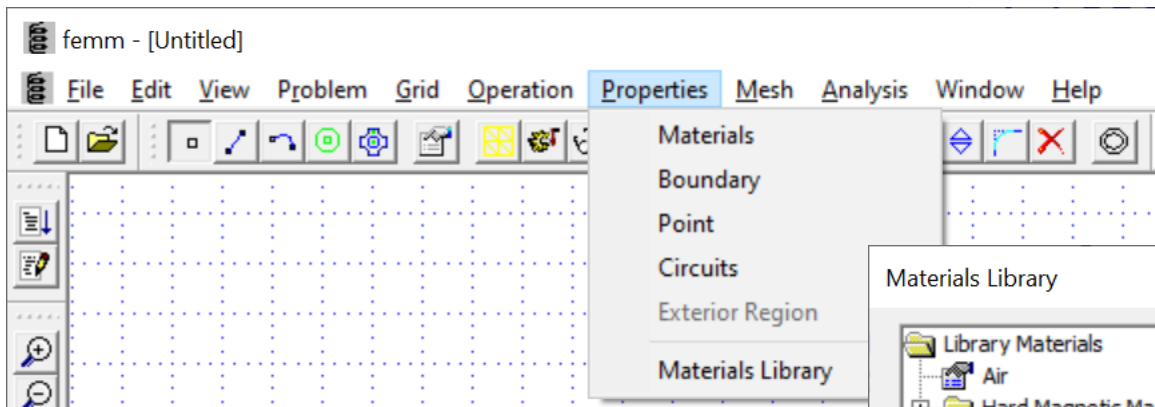
-- mm (aperture diameter)
-- mm (coil width)
-- deg
-- rad
-- mm (collar width)
-- mm
-- mm
-- needs to have fem extension

-- Input current density
Joverall = 385 --A/mm2
A_coil = alpha_coil/2*((aperture/2+w_coil)^2-(aperture/2)^2)
current = A_coil*Joverall -- A

-- Mesh parameters
mshf = 1
msh_yoke = 5*mshf
msh_collar = 8*mshf
msh_coil = 8*mshf
msh_ap = 1*mshf
msh_bck = 25*mshf
```



3. Material properties, boundary conditions and circuit elements



-- Material properties, from the available library

```
mi_getmaterial("Air")
mi_getmaterial("Pure Iron")
mi_getmaterial("Copper")
mi_getmaterial("316 Stainless Steel")
```

-- Create material for those not existing in the library

```
mi_addmaterial("NbTi", 1, 1,0, current,0,58,0,0,1,0)
```

3. Material properties, boundary conditions and circuit elements

Boundary Property ×

Name OK

BC Type Cancel

| | |
|---|--|
| <p>Small skin depth parameters</p> <p>μ, relative <input type="text" value="0"/></p> <p>σ, MS/m <input type="text" value="0"/></p> | <p>Prescribed A parameters</p> <p>A_0 <input type="text" value="0"/></p> <p>A_1 <input type="text" value="0"/></p> <p>A_2 <input type="text" value="0"/></p> <p>ϕ, deg <input type="text" value="0"/></p> |
| <p>Mixed BC parameters</p> <p>c_0 coefficient <input type="text" value="0"/></p> <p>c_1 coefficient <input type="text" value="0"/></p> | |
| <p>Air Gap parameters</p> <p>Inner Angle, Deg <input type="text" value="0"/></p> <p>Outer Angle, Deg <input type="text" value="0"/></p> | |

Boundary Property ×

Name OK

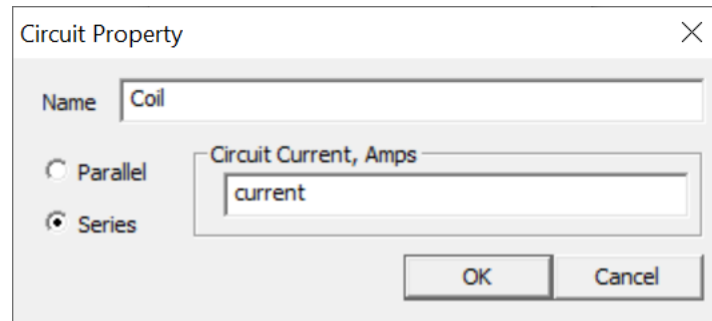
BC Type Cancel

| | |
|---|--|
| <p>Small skin depth parameters</p> <p>μ, relative <input type="text" value="0"/></p> <p>σ, MS/m <input type="text" value="0"/></p> | <p>Prescribed A parameters</p> <p>A_0 <input type="text" value="0"/></p> <p>A_1 <input type="text" value="0"/></p> <p>A_2 <input type="text" value="0"/></p> <p>ϕ, deg <input type="text" value="0"/></p> |
| <p>Mixed BC parameters</p> <p>c_0 coefficient <input type="text" value="0"/></p> <p>c_1 coefficient <input type="text" value="0"/></p> | |
| <p>Air Gap parameters</p> <p>Inner Angle, Deg <input type="text" value="0"/></p> <p>Outer Angle, Deg <input type="text" value="0"/></p> | |

-- Boundary conditions

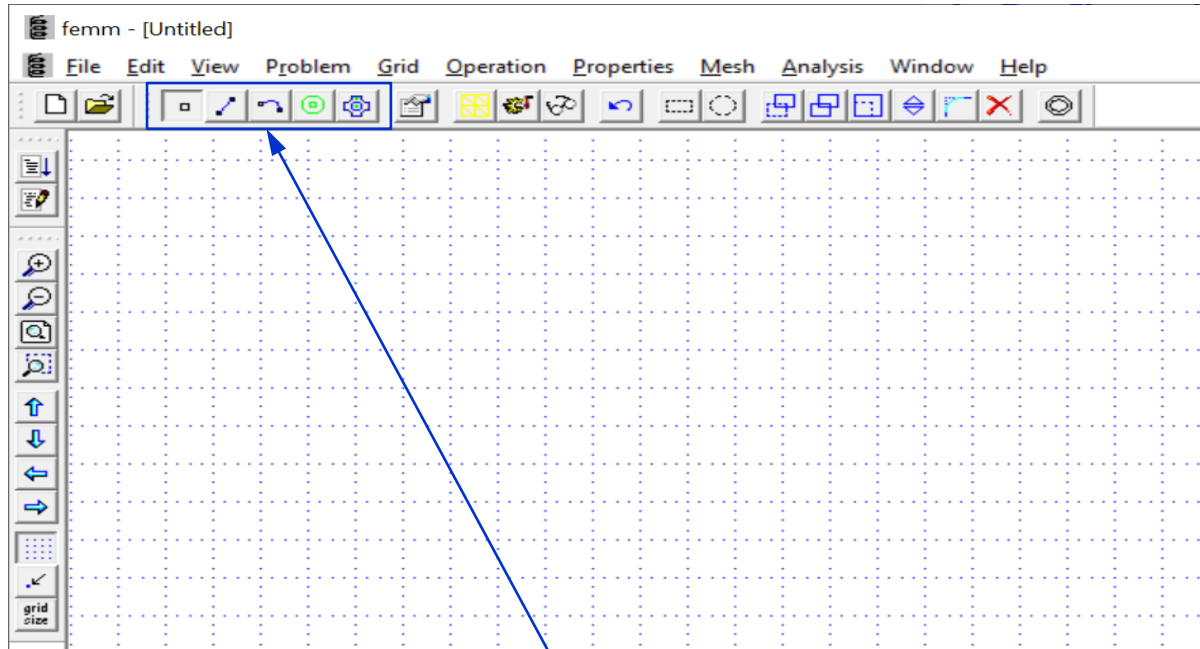
```
mi_addboundprop("B parallel", 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0)
```

```
mi_addboundprop("B perpendicular", 0, 0, 0, 0, 0, 0, 0, 0, 0, 2, 0, 0)
```



“current” is a previously defined variable,
alternatively you can enter a number

```
-- A circuit, multiple ones are possible
mi_addcircprop("Coil", current, 1)
```



via nodes, segments, blocks, etc...

Hot keys are particularly useful, also the grid can be handy

Previously defined variables can be used to describe the geometry

Copy and paste in the Lua console is also a possibility

Another approach is to import a DXF

```
-- Coil
```

```
x11_coil=aperture/2
y11_coil=0
x12_coil=aperture/2+w_coil
y12_coil=0
x13_coil=(aperture/2+w_coil)*cos(alpha_coil)
y13_coil=(aperture/2+w_coil)*sin(alpha_coil)
x14_coil=(aperture/2)*cos(alpha_coil)
y14_coil=(aperture/2)*sin(alpha_coil)
```

```
mi_addnode(x11_coil,y11_coil)
mi_addnode(x12_coil,y12_coil)
mi_addnode(x13_coil,y13_coil)
mi_addnode(x14_coil,y14_coil)
```

← nodes

```
mi_addsegment(x11_coil, y11_coil, x12_coil, y12_coil)
mi_addarc(x12_coil, y12_coil, x13_coil, y13_coil, alphas_coil, 1)
mi_addsegment(x13_coil, y13_coil, x14_coil, y14_coil)
mi_addarc(x14_coil, y14_coil, x11_coil, y11_coil, -alphad_coil, 1)
```

← segments

```
mi_addblocklabel((x11_coil+x12_coil)/2, 5)
mi_selectlabel((x11_coil+x12_coil)/2, 5)
mi_setblockprop("NbTi", 0, msh_coil, "Coil", 0, 0, turns)
mi_clearselected()
```

← blocks

Probably best to save before, in any case you need to save before you mesh

---> Mesh ---> Create Mesh

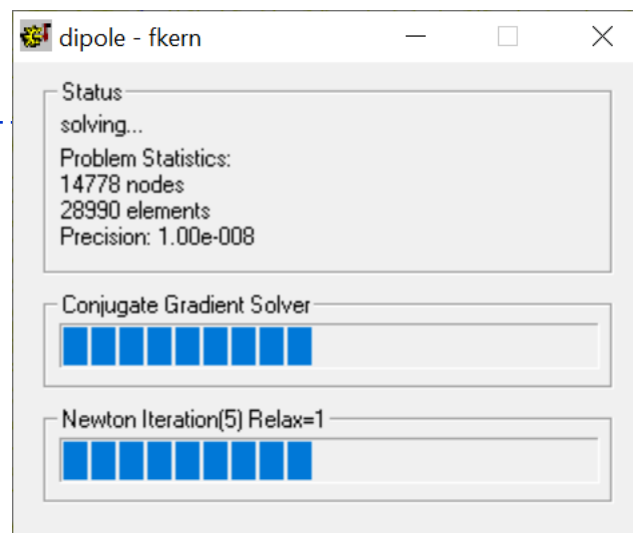


```

-- Save
mi_saveas(filename)

-- Mesh
mi_zoomnatural()
mi_createmesh()
    
```

---> Analysis ---> Analyze



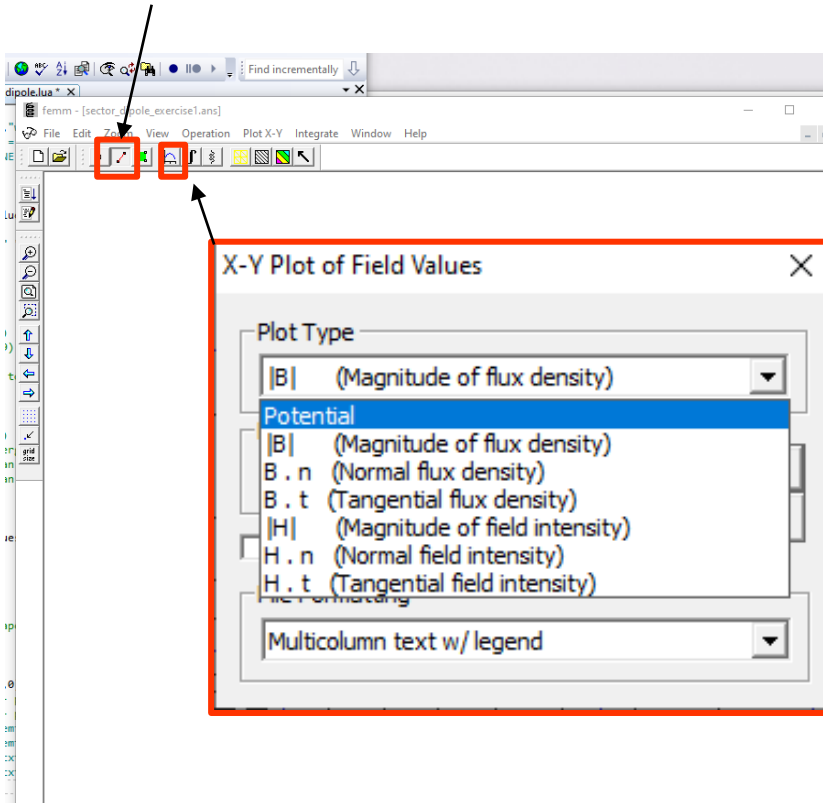
```
-- Solve  
mi_analyze()
```


---> Analysis ---> View Results



```
-- Post-processing  
mi_loadsolution()
```

Select a contour (right click in the mouse to add more points in your contour line; Esc to un-select the contour)



In LUA:

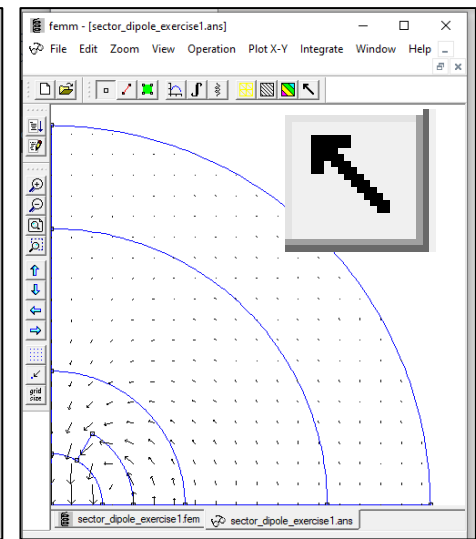
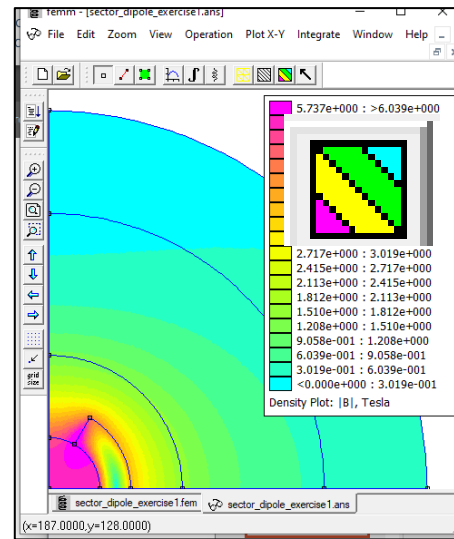
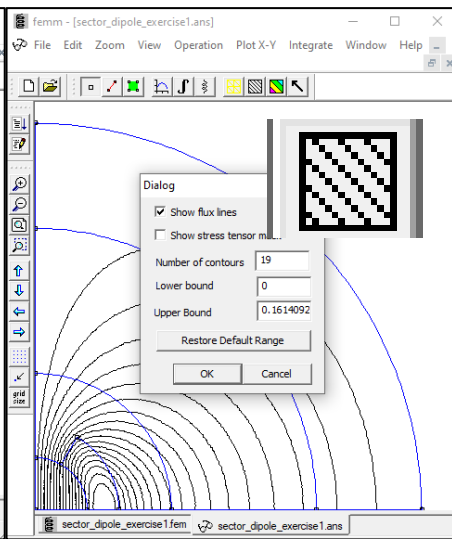
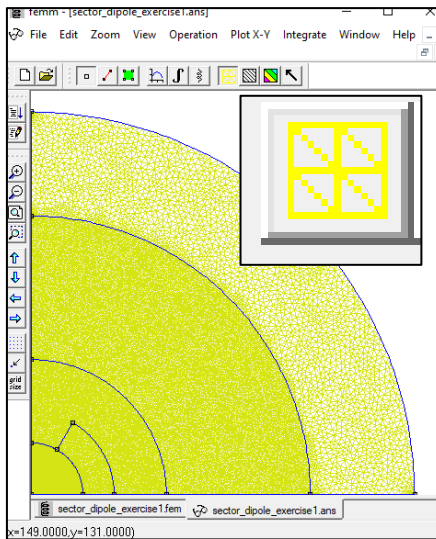
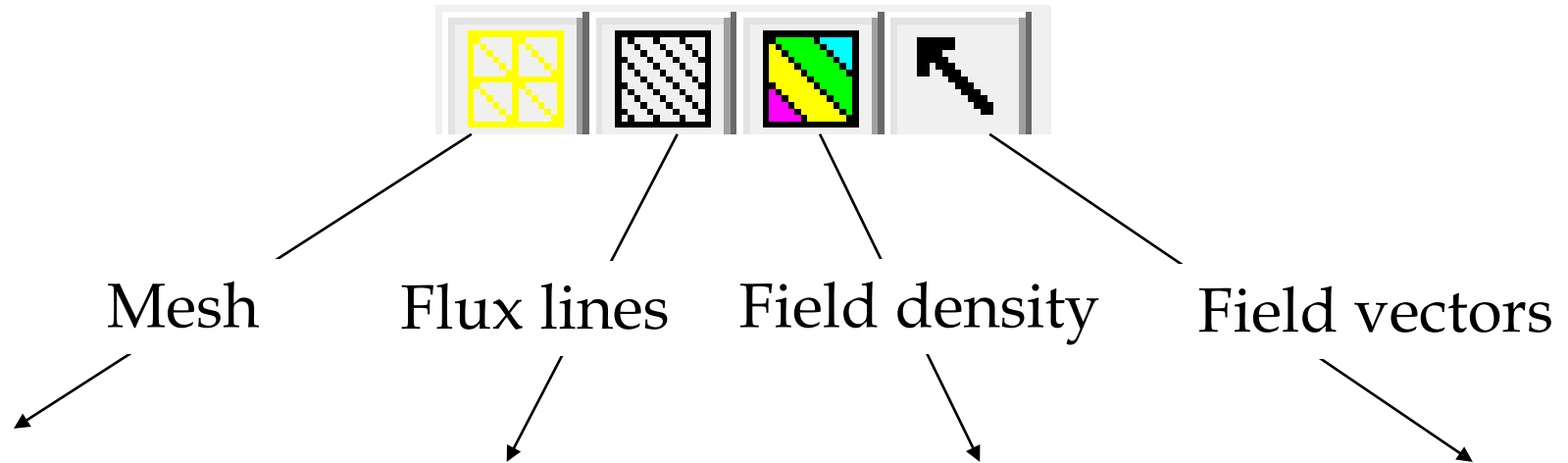
```

-----
-- Plot field in the aperture

-- Select a line
mo_addcontour(0,0)
mo_addcontour(aperture,0)
--mo_makeplot(2,200) -- plot in FEMM
--mo_makeplot(3,200) -- plot in FEMM
mo_makeplot(2,200,"Bx.emf") -- save image
mo_makeplot(3,200,"By.emf") -- save image
mo_makeplot(2,200,"Bx.txt",0) -- print it to a file
mo_makeplot(3,200,"By.txt",0) -- print it to a file
    
```

To script it in Lua, see <https://www.femm.info/Archives/doc/manual42.pdf> section 3.4 (Magnetics Post Processor Command Set)

7. Post-Processing: 2D plots.

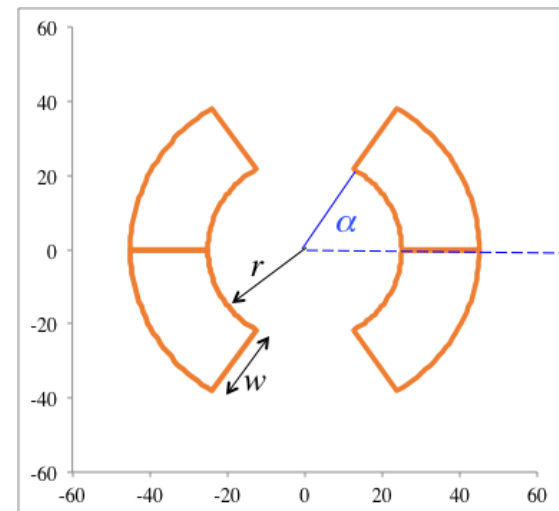


The screenshot shows the ANSYS FEMM software interface. The 'Integrate' menu option is highlighted in the top menu bar. The 'Block Integrals' dialog box is open, displaying a list of integration options. The 'Lorentz force ($\mathbf{J} \times \mathbf{B}$)' option is selected. The 'Integral Result' dialog box is also open, showing the following data:

| Component | Value |
|-------------|------------|
| x-component | 461.762 N |
| y-component | -456.876 N |

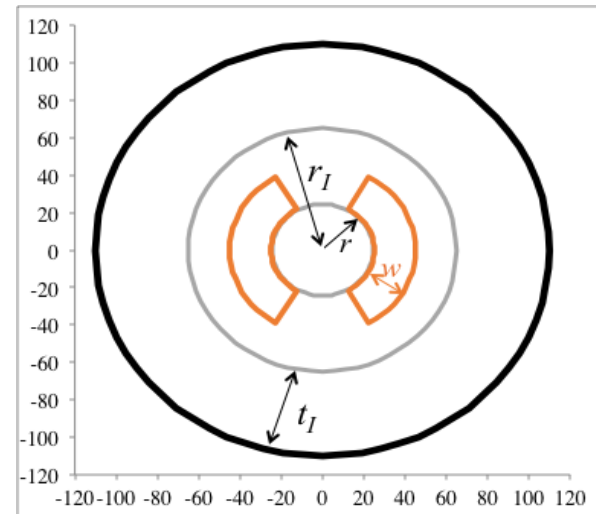
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 - **Exercise**
 - (script and solution in separate files)

- Exercise 1: We consider a dipole made as a 60° sector coil, with 50 mm aperture (diameter) and 15 mm width cable, without iron as in the exercise 1 of Day 1
 - Estimate via FEMM the overall current density needed to have a 5 T bore field, and compare to the analytical values;
 - Compute the field harmonics b_3 , b_5 and b_7 , using 17 mm as reference radius, and compare to the analytical values;
 - Verify how b_3 approaches to zero with finer meshes;
 - Verify that your solution does not change when increasing the size of the air region, and what is the minimum amount of air you need around the coil to have a converged solution



- Exercise 2:

- Estimate via FEMM the relative field increase due to the presence of iron with 65 mm inner radius and 134 mm outer radius and compare to the analytical values;
- Keeping the same 5 T field, estimate via FEMM the reduction of the current density given by the iron contribution compare to the analytical values;
- In this last case, estimate via FEMM the field in the midplane at 140 mm and at 200 mm from the magnet centre; if the field at 140 mm is larger than 5 mT, estimate the required increase in thickness to have less than 5 mT at 140 mm from the centre

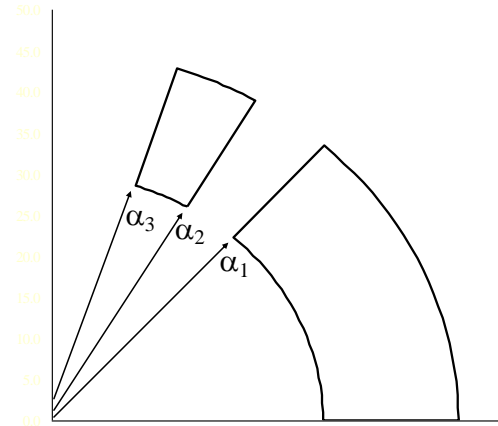


- Exercise 3:
 - Estimate via FEMM the peak field in the coil;
 - Estimate via FEMM the pressure given by the accumulation of azimuthal stress in the midplane, for the case without iron and with iron, and compare to the analytical values;
 - Estimate via FEMM the stored energy. What fraction of the energy is in the air/coil/collar/iron?
- Congratulations, you completed the exercise 😊
- A good time to look at your results and play a bit with the model?
 - How the field quality in the aperture and peak field in the coil changes as a function of the current?
 - What if you reduce the collar thickness to 10 mm? How the bore field to peak field ratio changes? And what about b_3 ?
- If you still have some time, try out the extra exercises

- For a coil with 2 blocks, one can find solutions to set to zero B_3 and B_5

$$B_3 = \frac{\mu_0 j R_{ref}^2}{\pi} \frac{\sin 3\alpha_3 - \sin 3\alpha_2 + \sin 3\alpha_1}{3} \left(\frac{1}{r} - \frac{1}{r+w} \right)$$

$$B_5 = \frac{\mu_0 j R_{ref}^4}{\pi} \frac{\sin 5\alpha_3 - \sin 5\alpha_2 + \sin 5\alpha_1}{5} \left(\frac{1}{r^3} - \frac{1}{(r+w)^3} \right)$$



- Note: we have to work with **non-normalized multipoles**, which can be added together

- Equations to set to zero B_3 and B_5

$$\begin{cases} \sin(3\alpha_3) - \sin(3\alpha_2) + \sin(3\alpha_1) = 0 \\ \sin(5\alpha_3) - \sin(5\alpha_2) + \sin(5\alpha_1) = 0 \end{cases}$$

- One can compute numerically the solutions

- $[0^\circ-24^\circ, 36^\circ-60^\circ]$
- $[0^\circ-36^\circ, 44^\circ-64^\circ]$
- $[0^\circ-48^\circ, 60^\circ-72^\circ]$
- $[0^\circ-52^\circ, 72^\circ-88^\circ]$

- Modify the coil geometry in the FE model to have a 2 blocks coil:

- Compare the harmonics to the 1 block coil
- Find the required coil width to reach the same field in the aperture

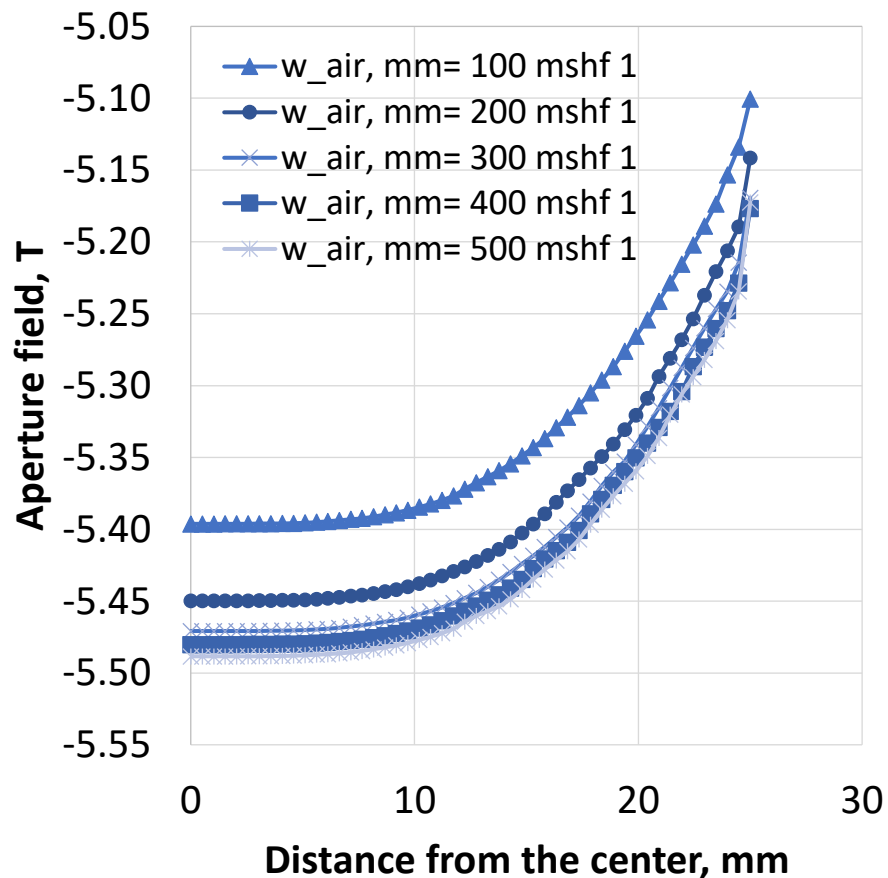
- Typically, finite element methods are best suited to problems with well-defined, closed solution regions. However, a large number of problems that one might like to address have no natural outer boundary. The boundary condition that one would like to apply is $A = 0$ at $r = \infty$.
- Fortunately, there are methods that can be applied to get solutions that closely approximate the “open boundary” solution using finite element methods. FEMM provides different options, look to the manual ([link](#)) and test the different options (section 1.3.1 and annex A3)

- You should be able to open and edit *.lua scripts in any text editor
- If you really like when the editor is helping you with colors to guide, you can:
 - Download TextPad <https://www.textpad.com/download#v9>
 - Download lua.syn file in <https://www.textpad.com/pt/addons/syntax-h2m>
 - Copy the file to the textpad system folder (typically would be C:\Program Files\TextPad 8\system)
 - Create a new document class in textpad (Configure/New Document Class...)

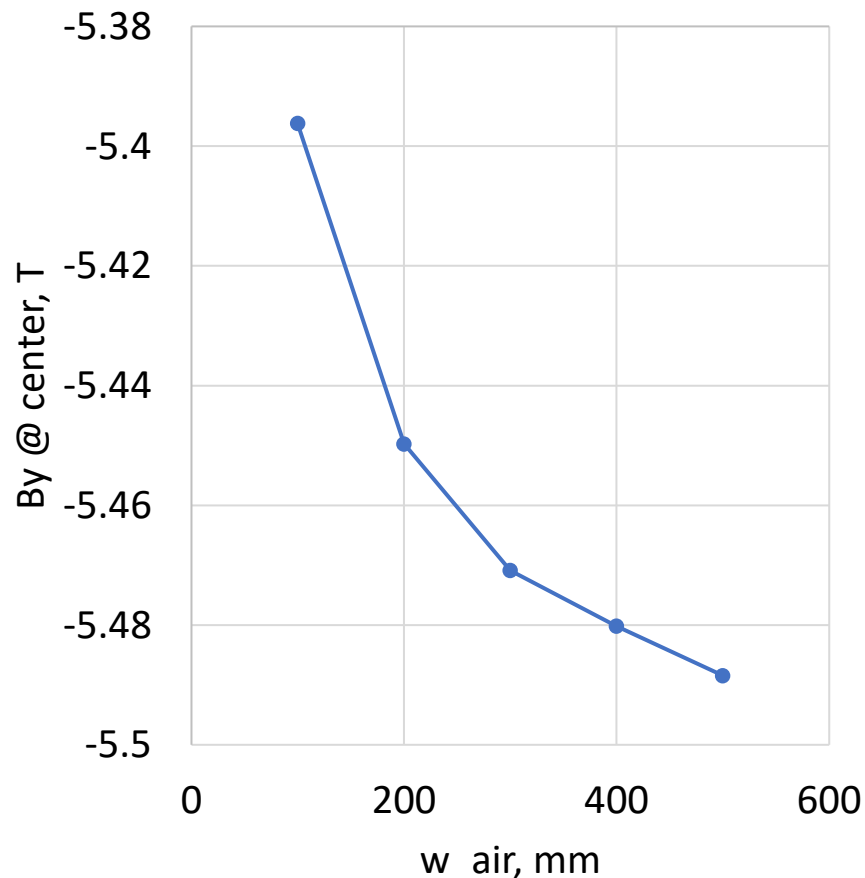
Solution discussion

- FEMM
 - no iron – find current
 - multipoles
 - Refine mesh to get b3 0

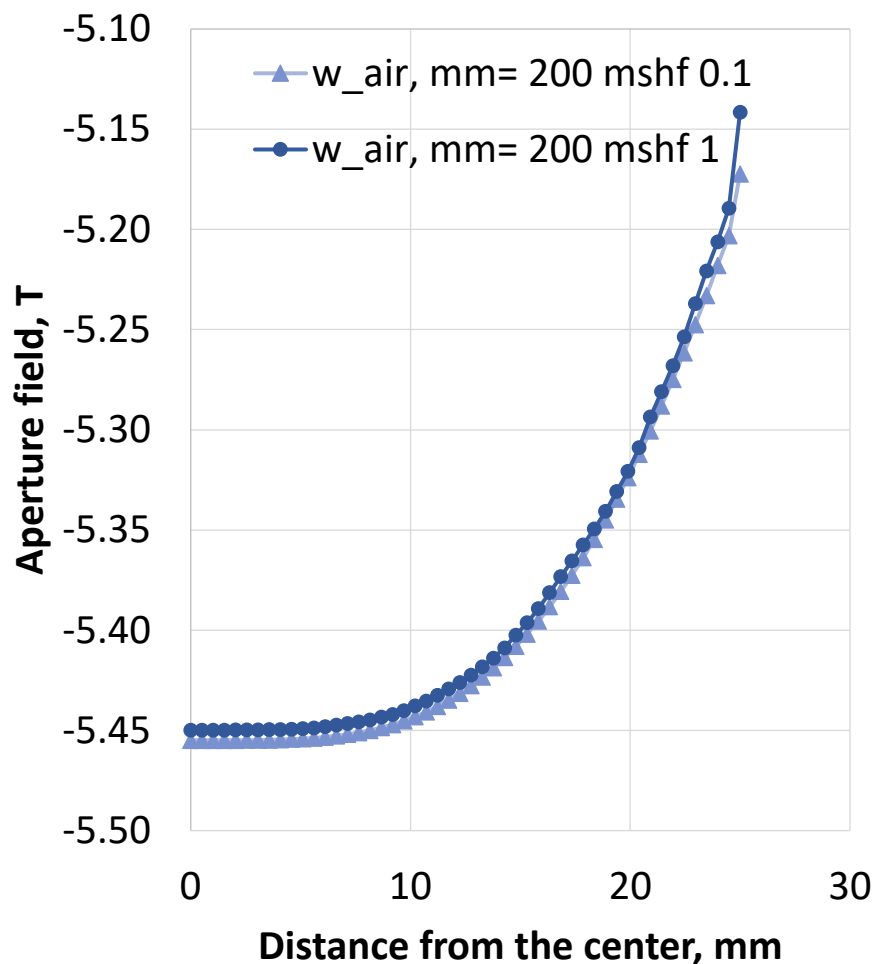
Convergence study - size of the air around



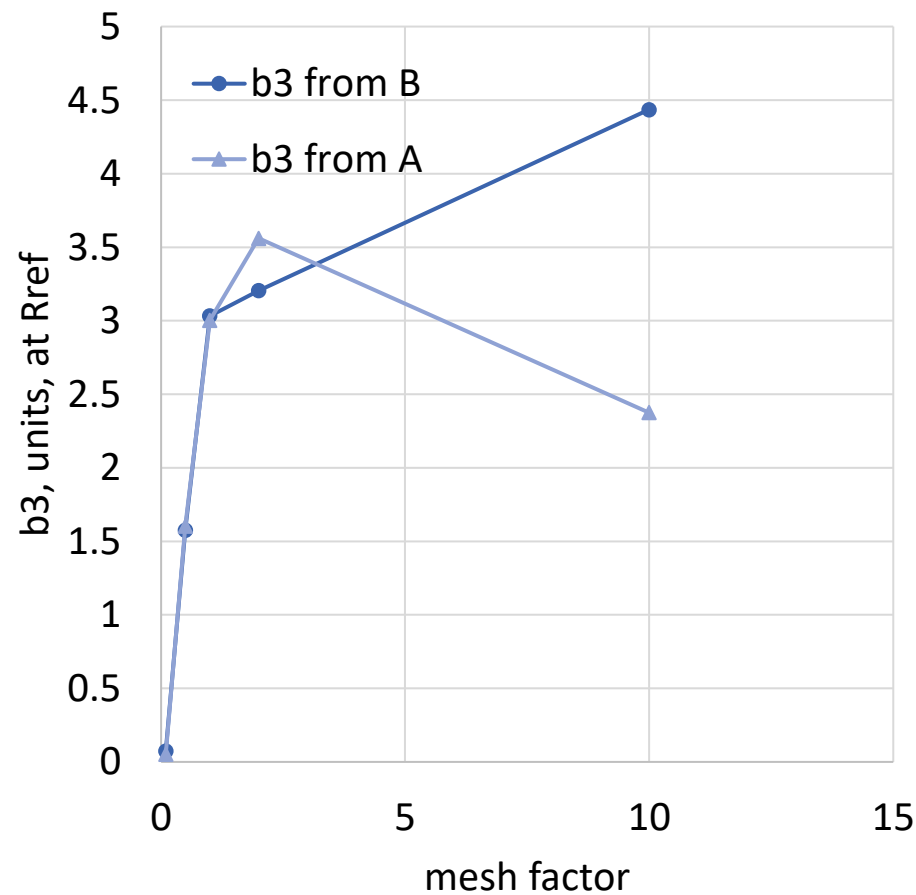
Convergence study - size of the air around



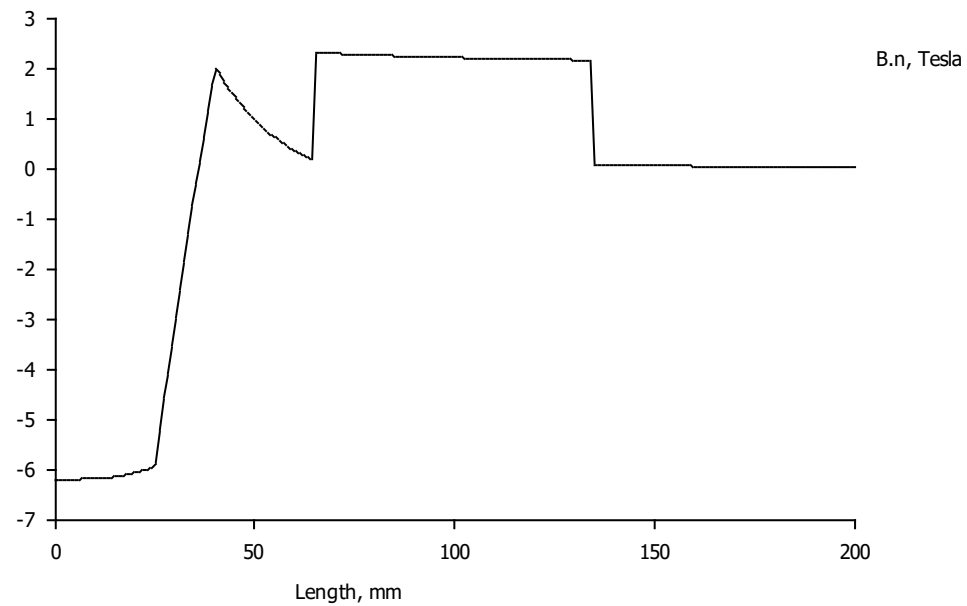
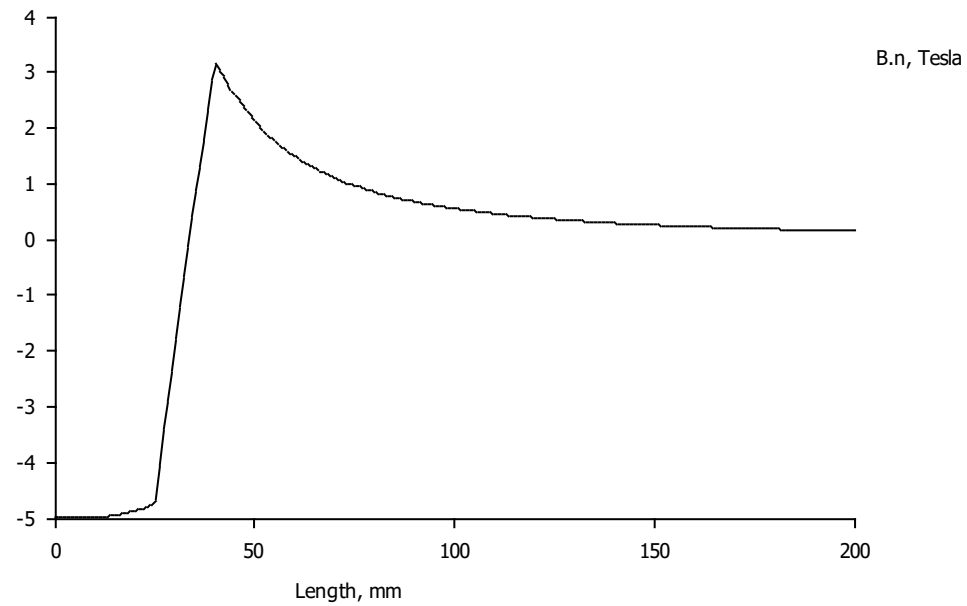
Convergence study - mesh size



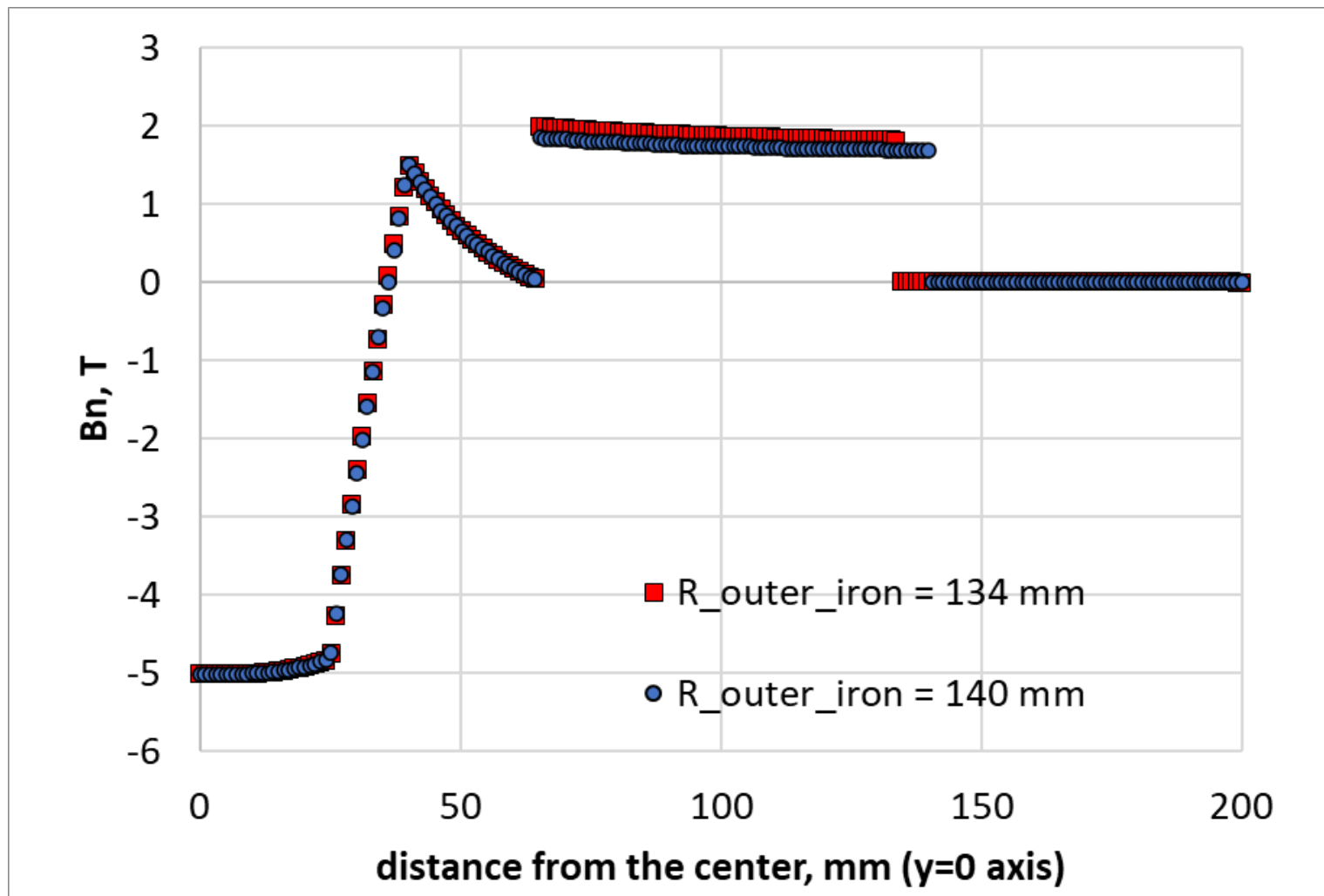
Convergence study - mesh size

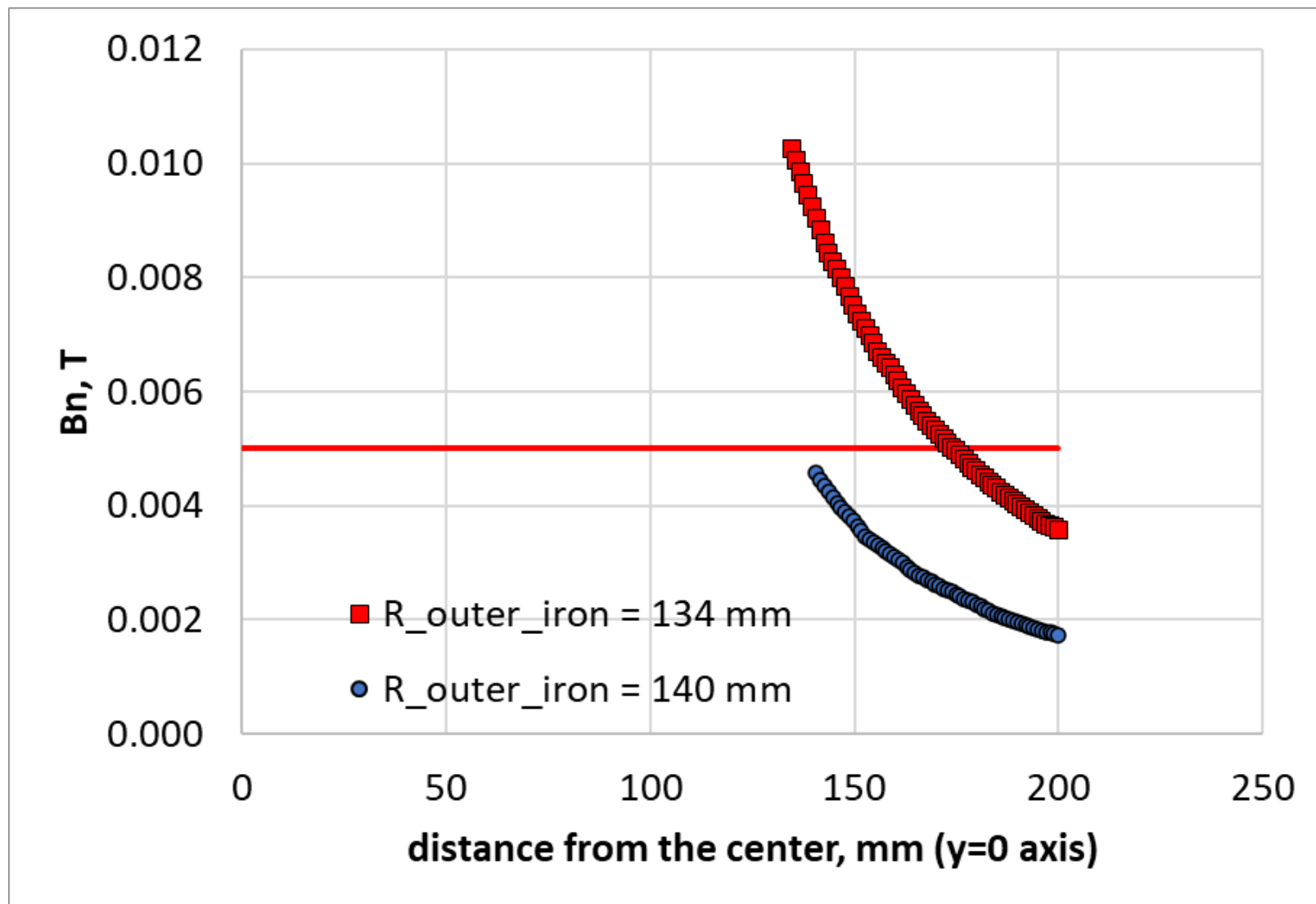


- FEMM
 - Back to normal mesh
 - Iron, we get more field



- FEMM
 - Current for 5 T
 - Shield condition



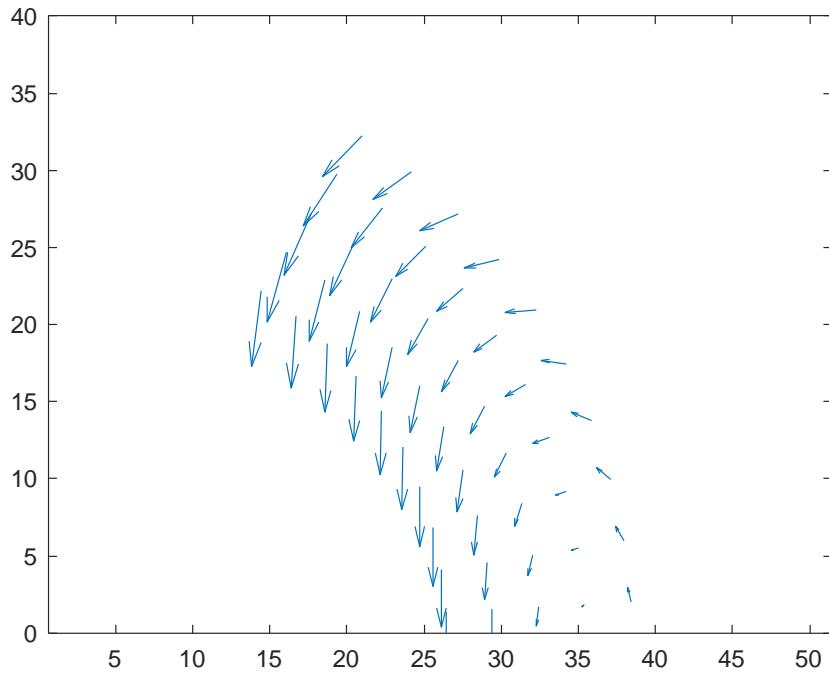


- FEMM
 - Peak field
 - Stored energy

| Stored energy sharing - case with iron | | | |
|---|------|------|----|
| Air in the aperture | kJ/m | 4.90 | 46 |
| Coil | kJ/m | 0.81 | 8 |
| Collar | kJ/m | 4.93 | 46 |
| Yoke | kJ/m | 0.01 | 0 |
| Air outside | kJ/m | 0.00 | 0 |
| Total | kJ/m | 10.6 | |

Stored energy density J/mm³ 0.021

B



$$\vec{F} = \vec{j} \times \vec{B}$$

